PROCEEDINGS, TOUGH Symposium 2006
Lawrence Berkeley National Laboratory, Berkeley, California, May 15–17, 2006

COUPLING TOUGH2 WITH CLM3: DEVELOPING A COUPLED LAND SURFACE AND SUBSURFACE MODEL

Lehua Pan, Jiming Jin, Norman Miller, Yu-Shu Wu, and Gudmundur Bodvarsson

Earth Sciences Division, Lawrence Berkeley National Laboratory
One cyclotron Road
Berkeley, California, 94583, USA
e-mail: lpan@lbl.gov

ABSTRACT

An understanding of the hydrologic interactions among atmosphere, land surface, and subsurface is one of the keys to understanding the water cycling system that supports life on earth. The inherent coupled processes and complex feedback structures among subsystems make such interactions difficult to simulate. In this paper, we present a model that simulates the land-surface and subsurface hydrologic response to meteorological forcing. This model combines a state-of-the-art land-surface model, the NCAR Community Land Model version 3 (CLM3), with a variably saturated groundwater model, TOUGH2, through an internal interface that includes flux and state variables shared by the two submodels. Specifically, TOUGH2 uses infiltration, evaporation, and root-uptake rates, calculated by CLM3, as source/sink terms in its simulation; CLM3 uses saturation and capillary pressure profiles, calculated by TOUGH2, as state variables in its simulation. This new model, CLMT2, preserves the best aspects of both submodels: the state-of-the-art modeling capability of surface energy and hydrologic processes (including snow, runoff, freezing/melting, evapotranspiration, radiation, and biophysiological processes) from CLM3 and the more realistic physical-process-based modeling capability of subsurface hydrologic processes (including heterogeneity, three-dimensional flow, seamless combining of unsaturated and saturated zone, and water table) from TOUGH2. The preliminary simulation results show that the coupled model greatly improved the predictions of the groundwater table, evapotranspiration, and surface temperature at a real watershed, as evaluated using 18 years of observed data. The new model is also ready to be coupled with an atmospheric simulation model, to form one of the first top of the atmosphere to deep-groundwater atmosphere-land-surface-subsurface models.

INTRODUCTION

The land surface often becomes the boundary between different disciplines in the scientific and engineering community, because of different modeling objectives. For example, many climate models, surface-water models, and vegetation/ecology models often take the land surface as the lower boundary, parameterizing the subsurface processes in various simplified ways (e.g., runoff coefficient, evaporation coefficient). On the other hand, many physically based subsurface or groundwater models often take the land surface as the upper boundary by lumping the complex processes above the surface as known boundary conditions (e.g., net infiltration or hydraulic head). However, such simplified models cannot properly describe how the real system behaves, in many cases resulting in unacceptable errors. During the last few decades, much progress has been made in development of more realistic models to simulate hydraulic interactions through the land surface. Instead of simply taking the land surface as the boundary of the modeling domain, many models simulate the lower portion of the atmosphere and upper portion of the subsurface as an integrated system, by which the atmosphere-land interactions become internal processes (Abromopoulos et al., 1988; Famiglieti and Wood, 1991; Wood et al., 1992; Liang et al., 1994; Bonan, 1998; Dai and Zeng, 1997; Walko et al., 2000; Liang et al., 2003; Olesen et al., 2004). CLM3 is one such model primarily developed to meet the needs of regional climate modeling. In CLM3, radiation, sensible and latent heat transfer, zonal and meridional surface stresses, and ecological and hydrological processes are simulated as interrelated subprocesses, using hybrid approaches (i.e., combinations of physically based dynamic modeling and empirically based parameterization models). However, the model of subsurface moisture flow in CLM3 is still overly simplified. In this regard, TOUGH2 can offer more realistic physical process-based modeling capability of subsurface hydrologic processes (including heterogeneity, three-dimensional flow, seamless combining unsaturated and saturated zones, and water table). Therefore, coupling these two models is an attractive way to build a useful model of surface-subsurface hydraulic interactions.

The objectives of this study are (1) to improve CLM3 simulation of important atmosphere-land interaction flux, such as ET, runoff, and latent heat flux by incorporating the sophisticated subsurface modeling capabilities of TOUGH2; (2) to extend the modeling capability of TOUGH2 to include the important energy, momentum, and moisture dynamics above the land surface provided by CLM3; and (3) to provide a sophisticated modeling tool of atmosphere-land-subsurface hydraulic interactions at watershed or regional scales, either as a stand-alone model or as part of an integrated model that ranges from the atmosphere all the way down to deep groundwater.

MODELING APPROACHES

The new model, CLMT2, is a combination of CLM3 and TOUGH2 (module EOS9 only, called as TOUGH2 below for simplicity) that is sequentially coupled. A detailed technical description of CLM3 can be found in the NCAR Technical Note (Oleson et al., 2004), whereas Wu et al. (1996) provided a summary of an unsaturated/saturated water flow simulation module (EOS9) within the TOUGH2 package.

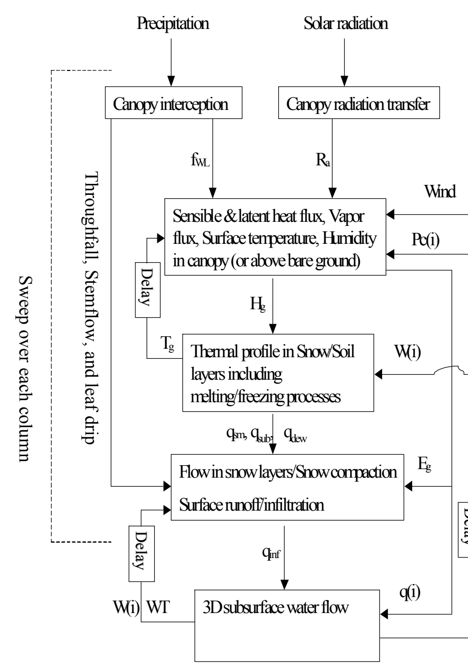
From the perspective of CLM3, the new model no longer simulates the subsurface moisture movement as a one-dimensional process by an explicit scheme. Instead, the 3-D Richards equation is solved implicitly by TOUGH2. In particular, the assumptions that the permeability decreases exponentially from top to bottom of the soil and that the groundwater is above the lower boundary are no longer used. Therefore, CLMT2 can be more flexible in dealing with complex subsurface environments. From the perspective of TOUGH2, the new model no longer takes the net infiltration or root uptake as prescribed boundary condition or source/sink terms. Instead, they result from simulations of coupled energy, wind, vegetation, and hydraulic processes by CLM3. As a result, CLMT2 expands the scope of TOUGH2 such that more realistic modeling of land-surface conditions is possible.

Spatial discretization and grid structure of CLMT2

The modeling domain below the land surface is discretized into connected grid cells similar to a TOUGH2 grid. In contrast to a regular TOUGH2 grid, the grid cells in the upper portion (the root zone) of a CLMT2 grid must be geometrically "regular" so that they can form grid columns. The aeral extent of each grid column corresponds to the grid cell of a regional climate model. Above each grid column, nested hierarchical grid structures are created to capture land-surface heterogeneity within the area. An area can contain multiple, noninteractive "Landunits" (e.g., "Glacier", "Wetland", "Vegetated", "Lake", and/or "Urban"). Each "Landunit" (except "Lake") can contain multiple, noninteractive "Snow/Soil" sub-columns. Similarly, each "Snow/Soil" type can contain multiple, noninteractive PFTs ("Plant Functional Type"). The term "noninteractive" indicates that there is no communication among substructures at the same level. In other words, they are logically isolated subareas with certain percentages. Besides the "Snow/Soil" subcolumns, which can have multiple layers, all other substructures are one-layer or single-node structures. Note that the "Soil" subcolumns spatially overlap the root zone of the subsurface grid column where the communication between TOUGH2 and CLM3 takes place. In addition, the "Snow/Soil" subcolumns are also used for calculations of thermal transfer and freezing/melting processes in snow cover and soil, because EOS9 of TOUGH2 does not account for those processes.

Modeling of processes in CLMT2

Figure 2.1 shows a brief flow chart of CLMT2 for one time step. For a given meteorological forcing at each time step, CLM3 modules simulate canopy and surface processes sequentially and column by column, using the water table (WT), water content (W(i)), and capillary pressure (Pc(i))



f_{WL}—fraction of wet leaf; R_a—absorbed radiation flux; T_g,H_g—ground temperature and heat flux; q_{sm}, q_{sub}, and q_{dew}—water flux of snow melting, sublimation, and dew, E_g—evaporation at ground; q(i), W(i), and Pc(i)—root uptake flux, water content, and capillary pressure in root zone; WT—groundwater table; q_{inf}—net infiltration

Figure 2.1 Flow chart of CLMT2

by the TOUGH2 module at the previous time step. The resulting net infiltration rate (q_{inf}) and root uptake flux (q(i)) are then used as source/sink terms in subsurface flow simulation by the TOUGH2 module. Inherited from CLM3, CLMT2 still keeps the “Lake” module for simulating the processes of water-covered land without any modifications

Major differences between CLM3 and CLMT2

Table 2.1 Major differences in simulation subsurface flow between CLM3 and CLMT2

CLM	CLMT2
Assumes that saturated hydraulic conductivity Ks decreases with depth exponentially.	Ks is a part of user specified input parameters and can be spatially variable.
Richards equation is solved explicitly (no iteration in each time step).	Richards equation is solved fully implicitly.
Clapp and Hornberger relationships are used for hydraulic functions of soil.	van Genuchten relationships are used for hydraulic functions of soil.
Hydraulic properties are assigned generally based on the soil texture classification.	Hydraulic properties are provided as input by the user for the specific site.
Soil moisture stress for root uptake is either 0 or 1 (dead or live).	A piecewise linear function is used to simulate the soil moisture stress for root uptake.
Soil columns are isolated from one another and subsurface drainage (base flow) is calculated as a value proportional to the saturation weighted average Ks in lower soil layers and exp(- WT), which is then deducted from the soil each time step.	Lateral subsurface flow if any is included naturally in three-dimensional flow simulation. No artificial subsurface drainage is included.
Soil depth is limited to 3.5 meters.	Soil depth, usually larger than 3.5 meters, is specified by the user so that the domain bottom is deeper than the groundwater table.

RESULTS AND DISCUSSION

Usadievsky Watershed, Valdai, Russia, is a midlatitude grassland catchment, with deep snow cover in the winter and significant precipitation in the summer. Its 18 years of observation data were used extensively within the Project for Intercomparison of Land-surface Parameterization Scheme (PILPS) and provided a very robust validation for surface-subsurface models (Maxwell and Miller, 2005). The hydraulic parameters used in this study are the same as those in Maxwell and Miller (2005). The entire catchment (0.36 km^2) is simulated as a 1-D column down to the depth of 6 m, which is below the minimum groundwater table in the site. All of the observations were made available by Robock et al. (2000) and Luo et al. (2003) as part of the Global Soil Moisture Databank. The precipitation data within the original meteorological forcing data in 3 hr interval were scaled by the observed monthly precipitation, so that the precipitation as model input was consistent with the observed at temporal scale of month. Table 3.1 lists the major model parameters used in the simulation.

Table 3.1 Model parameters used in Valdai simulation.

Parameter	**Value**	**Unit**
van Genuchten alpha	1.95	m^{-1}
van Genuchten exponent	1.74	
Saturated hydraulic conductivity	1.21	m/day
Effective soil porosity	0.401	m^3/m^3
Residual saturation	0.136	
Lower critical point at which root uptake stops	-5270.81	mm H2O
Upper critical point at which root uptake stops	0.1	mm H2O
Fraction of model area with high WT	0.15	
Latitude	57.6N	Degree
Longitude	33.1E	Degree
Vegetation type index	7 (grassland)	
Soil type index	6 (loam)	

The simulated daily snow depths are presented in Figure 3.1. Both CLM3 and CLMT2 predict almost identical results that agree well with the measured snow depth (the dots). This convergence between the two models is expected because of the halt in surface-subsurface hydraulic interactions during the frozen winter season. As a result, the accuracy of the subsurface simulation does not matter in simulating the snow accumulation process on the land surface.

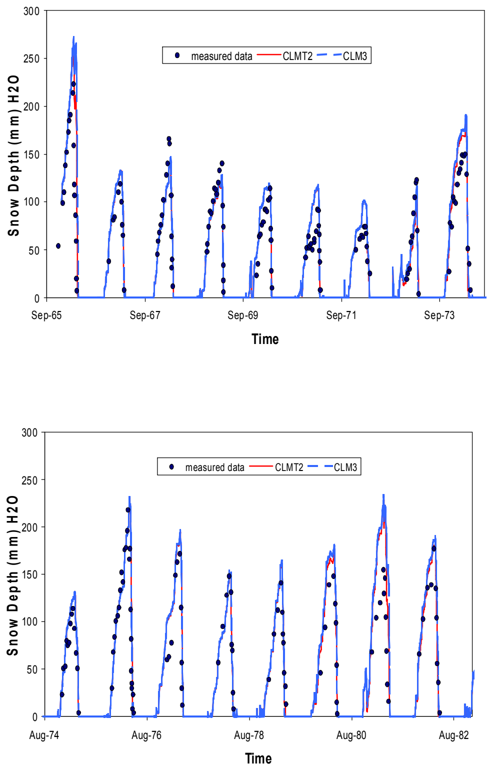


Figure 3.1 Simulated and observed snow depth (upper:1966-1973; below: 1974-1982)

However, CLMT2 does significantly improve the predictions of monthly evapotranspiration (ET) (Figure 3.2). As shown in Figure 3.2, CLM3 underestimated the ET compared with the measured data, while CLMT2 agrees well with the measure

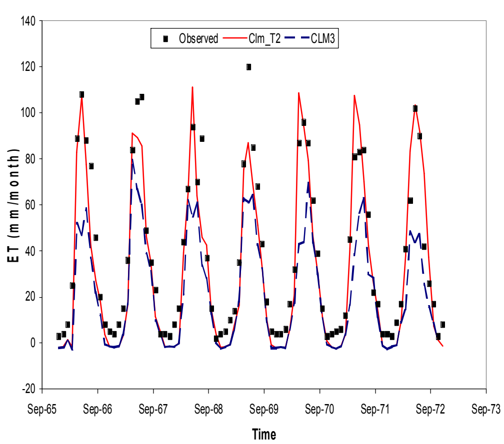


Figure 3.2 Simulated and observed monthly ET

data. Consistent with the underestimating of ET, CLM3 often overestimates the surface temperature during the summer season (Figure 3.3). Obviously, the coupled model, CLMT2, is more accurate in this case as well. These results indicate that the impact of subsurface flow on the surface processes during nonfrozen seasons is significant, and that correctly simulating the subsurface flow is very important.

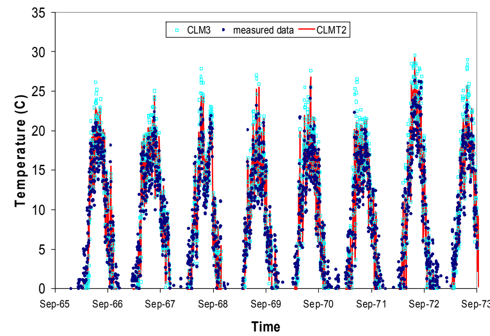


Figure 3.3 Simulated and observed daily ground surface temperature

Figure 3.4 compares the observed daily water tables (WT) with those simulated by CLM3 (blue line) and CLMT2 (red line), respectively. The observed WT data are a site average of 19 observation wells at a subweek scale. CLM3 uses a special parameterization scheme to calculate the WT from the wetness of the soil profile while the WT is automatically determined as the interface between the unsaturated and saturated soil layers simulated by CLMT2. As shown in Figure 3.4, CLMT2 replicated most groundwater seasonal responses to the meteorological forcing. CLM3, however, poorly estimated such responses, especially in magnitude of WT variations.

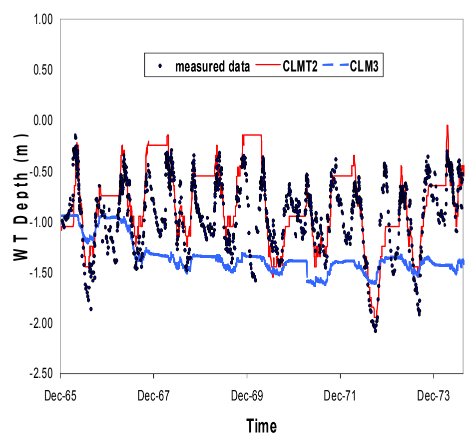


Figure 3.4(a) Simulated and observed daily groundwater table (WT).(1966-1974)

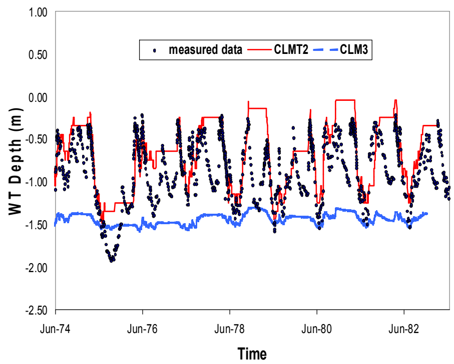


Figure 3.4 (b) Simulated and observed groundwater table (WT), (1974-1983)

Note that the models did not catch the decrease of water table during winter (Figure 3.4). This most likely is because the decrease of water table during winter is caused by regional water flow below the frozen zone, which cannot be accounted by the models that treated the entire catchment as a single column. A distributed model is required to investigate this problem and should be a good topic for further studies. Unlike CLM3, the new model, CLMT2, has the capability to simulate regional groundwater flow, provided that adequate field information is available.

CONCLUSIONS

A model that combines the ability to simulate the land-surface and subsurface hydrologic responses with meteorological forcing, CLMT2, has been developed by combining a state-of-the-art land surface model, the NCAR Community Land Model version 3 (CLM3), and a variably saturated groundwater model, TOUGH2, through an internal interface that includes flux and state variables shared by the two submodels. The 18 years of observed data in Usadievsky Watershed, Valdai, Russia, was used to evaluate the performance of the coupled model. Compared to CLM3, the new model, CLMT2, greatly improved the predictions of the water table, evapotranspiration, and surface temperature at the real watershed. This is particularly true in summer seasons when the interactions between surface and subsurface are significant. These results also indicate that correct simulation of subsurface flow (including the water table) is very important in simulation of surface processes such as evapotranspiration or land surface temperature, the two important feedback factors for regional climate.

REFERENCES

Abromopoulos, F., C. Rosenzweig, and B. Choudhury, Improved ground hydrology calculations for global climate models (GCMs): Soil water movement and evaporation. J. Climate, 1:921-941. 1988

Bonan, G. B., A Land Surface Model (LSM version 1.0) for ecological, hydrological, and atmospheric studies: Technical description and user's guide. NCAR Tech. Note NCAR/TN-417_STR, 1998

Clapp, R. B., and G. M. Hornberger, Empirical equations for some soil hydraulic properties. Water Resources Researches, 14:601-604, 1978.

Dai, Y. J., and Q.-C. Zeng, A land surface model (IA94) for climate studies. Part I: Formulation and validation in of-line experiments. Adv. Atmos. Sci., 14:433–460, 1997.

Famiglieti, J. S., and E. F. Wood, Evapotranspiration and runoff from large land areas: Land surface hydrology for atmospheric general circulation models. Surv. Geophys., 12: 179–204, 1991.

Liang, X., E. F. Wood, and D. P. Lettenmaier, A simple hydrolically-based model of land surface and energy fluxes for general circulation models. J. Geophys. Res., 99:14 415–14 428, 1994.

Liang, X., Z. Xie, and M. Huang, A new parameterization for surface and groundwater interactions and its impact on water budgets with the variable infiltration capacity (VIC) land surface model. J. Geophys. Res., 108: 8613, doi:10.1029 / 2002JD003090, 2003.

Maxwell, R. M., and N. L., Miller, Development of a Coupled Land Surface and Groundwater Model. J. of Hydrometeorology, 6:233-247, 2005.

Luo, L., and Coauthers, Effects of frozen soil on soil temperature, spring infiltration, and runoff: Results from the PILPS 2(d) experiment at Valdai, Russia. J. of Hydrometeorology, 4:334-351, 2003.

Oleson, K. W., and Coauthors, Technical Description of the Community Land Model (CLM). NCAR Technical Note/TN-461+STR 173 pp., 2004.

Robock, A., K. Ya. Vinnikov, G. Srinivasan, J. K. Entin, S. E. Hollinger, N. A. Speranskaya, S. Liu, and A. Namkhai, 2000, The Global Soil Moisture Data Bank. Bull. Amer. Meteor. Oc., 81:1281-1299, 2000.

Walko, R. L., and Coauthors, Coupled atmosphere–biophysics–hydrology models for environmental modeling. J. Appl. Meteor., 39:931–944, 2000.

Wood, E. F., D. P. Lettenmaier, and V. G. Zartarian, A land-surface hydrology parameterization with subgrid variability for general circulation models. J. Geophys. Res., 97(D3): 2717–2728, 1992.

Wu, Y.S., C.F. Ahlers, P. Fraser, A. Simmons, and K. Pruess, Software Qualification of Selected TOUGH2 Modules. Lawrence Berkeley National Laboratory Report: LBNL-39490, 1996.

ACKNOWLEDGEMENTS

The authors would like to thank Keni Zhang and Dan Hawkes for their review of this paper. Thanks are also due to Reed Maxwell for providing processed observation data and other assistance. This work was supported by the U.S. Department of Energy. The support is provided to Berkeley Lab through the U.S. Department of Energy Contract No. DE-AC03-76SF00098.